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The transmission of television signals in a narrow bandwidth using frequency modulation

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THE TRANSMISSION OF TELEVISION SIGNALS IN A NARROW BANDWIDTH USING FREQUENCY MODULATION

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SUMMARY

The use of frequency modulation for the transmission of television signals through a fused-quartz ultrasonic delay gives a high degree of gain stability and relatively low impairment due to spurious echoes. However, the bandwidth available in fused quartz delays of 1 ms delay and above is limited and may be less than twice the highest video modulating frequency. As a result, it may be necessary to transmit a frequency-modulated signal in which either the upper or lower sideband is partially suppressed. In this report, the performance of such narrow-band frequency-modulation systems is discussed and a practical system is proposed. The proposed system is designed to have a performance, as regards signal-to-noise ratio and picture impairment other than that due to echoes, which is comparable to that of an amplitude-modulated system occupying the same bandwidth. The investigation described was carried out in connection with the transmission of television signals through fused-quartz ultrasonic delays but the results are thought to have other applications; for example, in video tape recording. It should be pointed out that the theoretical discussion contains a considerable amount of material that is well known. However, it is necessary to include this material in order to present a complete and coherent account of narrow-band frequency modulation.

1. INTRODUCTION

Fused-quartz ultrasonic delays with carrier frequencies in the range 10 to 50 MHz are used in television applications where storage of the signal is required for periods ranging from the duration of a scanning line to the duration of a field. One important application occurs in a field-store standards converter[1] where the signals corresponding to various groups of scanning lines are transmitted through different combinations of fused-quartz ultrasonic delays. In this case it is necessary to match closely the performance parameters of the different ultrasonic delays in order that the signals corresponding to the various groups of scanning lines are equally affected by their transmission paths. If this condition is not met, spurious patterns of a regular and repeated nature will appear on the picture. In particular, it has been found in previous experiments[2] that equality of gain between different delay paths is very important and that adequate gain stability is extremely different to achieve if amplitude modulation (a.m.) of the carrier is used. The use of frequency modulation (f.m.) offers a solution to this problem since a high degree of gain stability can be achieved quite easily.

The bandwidth available in a fused-quartz delay is limited, particularly when the value of the delay is 1 ms or above. In a typical case, the bandwidth is approximately 7 MHz and is therefore insufficient to permit the transmission of a double-sideband (d.s.b.) signal of the European 625-lines, 50 field standard. The transmission of an a.m. signal in a bandwidth of 7 MHz presents no difficulty; vestigial-sideband (v.s.b.) transmission may be used. The use of f.m. in a bandwidth permitting only v.s.b. transmission requires some investigation, however, and the performance of a.m. and f.m. systems in these circumstances has therefore been compared. The comparison has been made in respect of the forms of distortion likely to be introduced by fused-quartz delays, namely: amplitude non-linearity, non-uniform response and group-delay as functions of frequency and spurious echoes.

In Section 2 and in the Appendix the theory of narrow-band f.m. transmission is discussed and it is shown that in some important respects there is little difference between a.m. and f.m. It is also shown that v.s.b. transmission of f.m. is possible and that f.m. therefore has no disadvantage when compared with a.m. in this respect. In Section 3 the effects of the distortions introduced by fused-quartz delays are discussed and in Section 4 the parameters are given for a v.s.b. f.m. system whose performance is comparable with that of an a.m. system occupying the same bandwidth.

It should be pointed out that the use of narrow-band f.m. for the transmission of television signals is not new; in fact, a v.s.b. system using f.m. is employed in video tape recorders. The techniques developed for video tape recording are not, however, entirely relevant to the problem of transmission through a fused-quartz delay. This is because, unlike the fused-quartz delay, a relatively low carrier frequency must be used in a video tape recorder and there is insufficient bandwidth below the carrier frequency to accommodate all the lower sidebands having significant amplitudes.[3]

2. NARROW-BAND FREQUENCY MODULATION

2.1. Instantaneous Frequency

The fundamental notion of frequency assumes a periodic waveform persisting over a very long time, there being sufficient numbers of identical repetitions of each cycle to make it possible to measure the frequency accurately. Thus it is not possible to consider a "varying frequency" without a definition of the term.

It is customary to define a quantity called "instantaneous frequency" as the rate of change of the phase $\theta(t)$, of a waveform represented by a complex function of time $r(t)\ e^{j\theta(t)}$. It is possible to design frequency modulators that produce radio frequency (r.f.) waveforms whose instantaneous frequency is proportional to the magnitude of the modulating signal and to design demodulators which give an output whose magnitude is proportional to the instantaneous frequency of the input r.f. waveform. Thus for all practical purposes the instantaneous frequency of the r.f. waveform can be regarded as the parameter which carries the modulating-signal information.

In cases where the bandwidth of the r.f. transmission path is very much greater than twice the highest frequency contained in the modulating signal, the instantaneous frequency of an f.m. signal is transmitted with very little distortion. The distortion of the instantaneous frequency depends on the magnitudes of the derivatives of the transfer function of the transmission path with respect to frequency and also on the highest frequencies in the modulating signal. It can be shown that, if the highest modulating frequencies transmitted are sufficiently low for the second and higher-order derivatives of the transfer function to be neglected, the response of the transmission path to a complex signal $e^{j(\omega_0 t + \theta(t))}$ of constant amplitude becomes:

$$f(j\omega_0 + j\,\theta'(t))\ e^{j(\omega_0 t + \theta(t))} \qquad (1)$$

where $f(j\omega)$ is the transfer function of the transmission path

$\omega_0/2\pi$ is the carrier frequency

$\theta(t)$ is the phase as a function of time and $\theta'(t)$, its derivative, is the instantaneous frequency.

Expression (1) is known as the "quasi-stationary approximation".[4,5] It will be seen, therefore, that if the signal is amplitude limited before demodulation so that variations of amplitude are removed, very little distortion will occur if the transmission bandwidth is such that Expression (1) is a close approximation to the actual output signal.

In the case of television transmission through a fused-quartz delay of value 1 ms or above, the video bandwidth is only a little less than the bandwidth of the transmission circuit. In this case the quasi-stationary approximation is only valid for low video modulating frequencies and the response to high video modulating frequencies must be analysed in terms of the sidebands of the r.f. signal.

2.2. Sideband Analysis

In considering the behaviour of a frequency-modulated r.f. signal, an important parameter is the "modulation index" which is defined as the ratio of the maximum deviation of the instantaneous frequency (from the nominal carrier frequency) to the frequency of the modulating signal. The waveform of an r.f. signal, frequency modulated by a sinusoidal video signal $a \cos \omega_1 t$ may be represented in complex form by the Expression:

$$S = e^{j(\omega_0 t + ka/\omega_1 \sin \omega_1 t)} \qquad (2)$$

where $\omega_0/2\pi$ is the carrier frequency, $\omega_1/2\pi$ is the modulating frequency, ka/ω_1, the modulation index, is the maximum deviation of phase due to modulation and k is a constant that converts units of amplitude of modulating function into units of frequency deviation.

Suppose now that the modulation index $\delta = ka/\omega_1$ is small (say, less than 0·1). Then to a first approximation the frequency-modulated signal of Expression (2) can be written as:

$$S = -\frac{\delta}{2} e^{j(\omega_0 - \omega_1)t} + e^{j\omega_0 t} + \frac{\delta}{2} e^{j(\omega_0 + \omega_1)t} \qquad (3)$$

Expression (3) shows that for a small modulation index, a frequency-modulated r.f. signal has a spectrum consisting of a carrier frequency term and two sidebands of equal amplitude, as in the case of an amplitude-modulated r.f. signal; the only difference between the frequency-modulated spectrum and the amplitude-modulated spectrum is that the phase of one of the sidebands is reversed in sign. As a result of this similarity in spectra, the effects of varying transmission characteristics are similar. It is shown in the Appendix that, apart from second-order distortions and a gain factor, the effects of transmission-path response and group-delay irregularities are identical for, on the one hand, a.m. transmission with a small depth of modution and, on the other hand, f.m. transmission with a small modulation index.

For small values of the modulation index, only two sidebands are significant but, as the modulation index is increased, the higher-order sidebands become larger in magnitude. For example, when Expression (2) is expanded as a power series the term $\{\delta^2 \sin^2 \omega_1 t\}/2!$ gives rise to sidebands whose spacing from the carrier is twice the modulating frequency. If these second-order sidebands are of significant amplitude and are attenuated or phase shifted in transmission, the transmitted signal will be modulated in amplitude and phase and as a result the instantaneous frequency will be distorted.

2.3. Limitation of R.F. Bandwidth and its Effect on Frequency Deviation

For d.s.b. transmission of an f.m. signal the minimum possible bandwidth is twice the highest frequency in the modulating signal since it is necessary to transmit at least the first-order sidebands given in Expression (3); further, the deviation must be limited to such a value that no significant higher-order sidebands lie outside the transmission band. In the case of the 625-line, 50-field television standard with 5·5 MHz video-frequency bandwidth, the minimum r.f. bandwidth required for d.s.b. f.m. transmission is 11 MHz, as in a.m. The lowest video frequency for which the second-order sidebands lie just outside the 11 MHz band is approximately 3 MHz (the second-order sidebands will be spaced 6 MHz above and below the carrier frequency). In order to ensure that the distortion of the video signal is small, the deviation must be such that the second-order sidebands corresponding to a 3 MHz modulating frequency are small. For example, if it is assumed that the amplitude of the second-order sidebands must not exceed 5% of the unmodulated carrier amplitude, it may be shown that this corresponds to a modulation index of approximately 0·6. Thus, the maximum deviation of the instantaneous frequency at a modulating frequency of 3 MHz should not exceed ± 1·8 MHz. Similarly, figures may be deduced for the maximum permissible frequency deviation for lower video frequencies where the sidebands lying outside the transmission band have higher orders than the second. The figure of maximum deviation of ± 1·8 MHz, is, however, the most stringent of these requirements and therefore imposes a limit to the maximum deviation that may be used.

2.4. Vestigial Sideband Transmission of a Frequency-Modulated Signal

It is well known that adequate transmission of television signals is possible using a.m. if the higher-frequency sidebands on one side of the carrier frequency are suppressed leaving a vestigial sideband with a bandwidth of about 1 MHz. This form of transmission results in a useful saving of bandwidth and it would clearly be of value if a similar technique could be used for f.m. transmission.

Suppose that a frequency-modulated r.f. signal is transmitted through a channel having the idealised phase-corrected response/frequency characteristic shown in Fig. 1. If the modulation index is sufficiently low, the input signal will conform to Expression (3). If the modulating frequency $\omega_1/2\pi$ is such that the lower sideband is completely suppressed, the signal, after passing through the channel, becomes:

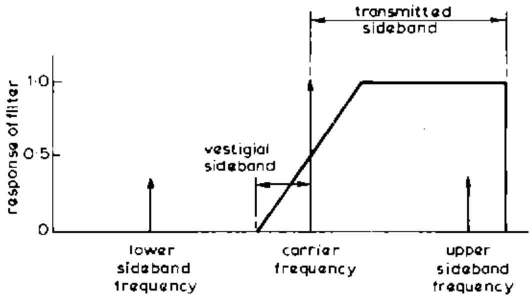

Fig. 1 - Ideal asymmetric sideband filter characteristic

$$S_1 = \frac{1}{2} e^{j\omega_0 t} + \frac{\delta}{2} e^{j(\omega_0 + \omega_1)t} \qquad (4)$$

Expression (4) represents a signal which is modulated in both frequency and amplitude but the amplitude modulation can be removed by a limiter. If the signal is then demodulated in a detector which gives an output whose magnitude is proportional to the instantaneous frequency, the demodulated output signal can be readily shown to be identical with the original modulation. Thus for modulating frequencies where one sideband is completely suppressed and the deviation is sufficiently low, the demodulated signal is undistorted. Similarly, by the form of analysis used in the Appendix it may be shown that for lower modulating frequencies whose sidebands fall on the sloping portion of the transmission characteristic of Fig. 1, the demodulated signal is also undistorted. However, the modulation index increases as the modulating frequency is reduced and an analysis in terms of lower order sidebands will not be valid for very low modulating frequencies. At these frequencies, however, the quasi-stationary approximation is valid since the bandwidth of the system is wide enough for the instantaneous frequency to be transmitted with negligible distortion. It may, therefore, be concluded that for a single modulating frequency, vestigial-sideband f.m. transmission may be used, provided that the frequency deviation is sufficiently small.

A television signal will consist, more generally, of a d.c. component and added sinusoidal components. The d.c. component will shift the frequency of the carrier from its nominal value so that it no longer lies at the -6 dB point of the v.s.b. characteristic of Fig. 1. Thus the ratios of the amplitude of the carrier to those of the sideband corresponding to a particular modulating frequency will depend upon the d.c. component and thus the amplitudes of the demodulated sinusoidal components will also depend upon the d.c. component. This distortion is similar to "differential gain" distortion due to non-linear transmission circuits in the case of a.m. transmission and will be particularly important for colour television transmission. The amount of differential gain distortion may be reduced by arranging that the frequency deviation is low at low modulating frequencies or by reducing the slope of the v.s.b. filter characteristic; the latter, of course, implies that the bandwidth required for transmission will be increased. Thus, in a v.s.b. system, the frequency deviation may need to be less than in the case of a d.s.b. transmission.

3. THE EFFECTS OF INTERFERENCE AND DISTORTION IN NARROW BAND F.M.

In assessing the application of f.m. as a transmission system for use with fused-quartz delays, a number of sources of interference and distortion must be considered. The forms of interference and distortion likely to occur in the transmission channel are:

(1) Random fluctuation noise.

(2) Effects of bandwidth restriction.

(3) Amplitude non-linearity (and variations of gain).

(4) Effects of variations of the response and group-delay characteristics of the transmission path with frequency.

(5) The presence of spurious echoes of the main signal.

It is of particular interest to compare the performance of v.s.b. f.m. and a.m. systems occupying the same bandwidth. The f.m. system which has been developed has therefore been compared directly with a corresponding a.m. system and the basis for comparison was a simulation of the conditions obtaining in a field-store standards conversion system. Some aspects of the relative performance of a.m. and f.m. systems could not conveniently be checked by experiment. The following comparisons are therefore based in part on experiment and in part on calculation.

3.1. Signal-to-Noise Ratio

In order to compare the signal-to-noise ratios obtainable with a.m. and narrow-band f.m. transmission systems, it is necessary to consider the relative amplitudes of the noise components and the sidebands corresponding to maximum sinusoidal modulation. In a.m., the sideband amplitude is independent of the modulating frequency, whereas in a narrow-band f.m. system, the sideband amplitude for constant frequency deviation varies inversely as the modulating frequency. As a result, radio frequency noise whose spectrum is of constant amplitude, results in a triangular video-frequency noise spectrum after demodulation.

It has been pointed out in Section 2.3 that the modulation index of a narrow band frequency-modulated r.f. signal must be limited in value and, as a consequence, the amplitudes of the sidebands are limited to values which may be less than those occurring in a.m. However, by using r.f. pre-emphasis at the modulator and r.f. de-emphasis immediately prior to the detector, the signal-to-noise ratio of the demodulated signal is improved and the relative amplitudes of noise and signal spectral components may be made approximately equal in a.m. and f.m. systems of similar bandwidth. It is not, however, advantageous to pre-emphasise the sidebands so that their amplitudes exceed that of the unmodulated carrier. This is because the peak level of the r.f. signal is then increased and any gain in signal-to-noise ratio is offset by a significant increase in total power. Experiments were carried out to assess the subjective effect of noise in v.s.b. a.m. and narrow-band f.m. systems and showed that in the absence of r.f.

pre- and de-emphasis the addition of equal amplitude r.f. noise resulted in a greater picture impairment in the case of f.m. However, the amounts of pre- and de-emphasis given in Section 4 were found to reduce the noise visibility so that the a.m. and f.m. systems became approximately equal in this respect.

3.2. Practical Values for Bandwidth and Deviation

For purposes of comparison, a.m. and narrow-band f.m. signals using a carrier frequency of 17 MHz were transmitted through a v.s.b. filter whose response/frequency characteristic is shown in Fig. 2. The filter had a bandwidth of approximately 7 MHz and a vestige bandwidth of approximately 2 MHz and was chosen because its response/frequency characteristic was typical of that of a fused-quartz delay of 1 ms or above. A 625-line, 50-field Test Card 'C' derived from a high-quality slide scanner was transmitted through the two systems and it was found that the quality of the picture was about equal for both systems provided that the maximum frequency deviation of the f.m. system did not exceed ± 1 MHz. As the deviation of the f.m. system was increased above ± 1 MHz, two forms of distortion appeared. Non-linear transient distortion occurred in which the overshoots following rapid changes of brightness become accentuated in a manner which depended on the amplitude of the change and its direction. When the deviation was further increased, transients and high-frequency detail in the picture appeared very noisy; this latter effect is difficult to explain but may be due to a failure of the limiter to produce a signal when the r.f. signal is momentarily reduced to zero.

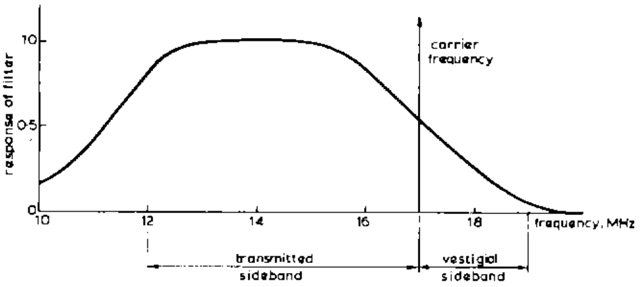

Fig. 2 - Characteristic of practical v.s.b. filter

3.3. Non-Linearity of the Transmission Path

For a.m., amplitude non-linearity in the signal transmission path causes distortion of the grey scale rendering, particularly in large areas, of a television picture. However, with f.m., the grey scale is unaffected by the non-linearity since, for very low video frequencies, the grey scale is determined by the instantaneous frequency which is unaffected by non-linearity. Thus f.m. is generally more tolerant to non-linearity in amplifiers than a.m. and is therefore suitable for use in the field-store conversion process where the signal is transmitted sequentially through alternative paths. In particular, any difference in the linearity of the paths which, in the case of a.m., would cause the switching pattern to be impressed on the picture as a variation of grey level is avoided. The use of f.m. therefore obviates the necessity for accurate linearity matching.

3.4. Variation of the Transmission Characteristic with Frequency

It is shown in the Appendix that except at very low modulating frequencies where a number of significant sidebands occur, the behaviour of a narrow-band f.m. system with very small deviation and an a.m. system with low modulation depth must be similar. In particular, variations of the response/frequency and group delay/frequency characteristics of a transmission path will affect an f.m. system of small deviation and an a.m. system with low modulation depth in exactly the same way.

In practice, however, the frequency deviation cannot be made arbitrarily small and as a result f.m. may suffer from differential-gain distortion if the response/frequency characteristic is non-uniform and differential phase distortion if the group delay/frequency characteristic is non-uniform. However, for monochrome transmissions, a deviation of about ± 1 MHz is possible for the group delay and amplitude changes likely to be encountered in a field-store converter provided that radio frequency pre- and de-emphasis are used. NTSC and PAL colour transmissions have been considered and it has been concluded that the deviation would need to be reduced if the differential phase and differential amplitude distortions are to be reduced to an acceptable level. The signal-to-noise ratio will therefore be worse than for a monochrome transmission unless the system is modified. The system can, in fact, be modified by an increase in radio frequency pre- and de-emphasis or by the addition of pre-emphasis of the video frequency input signal and de-emphasis of the demodulated output signal. Either of these changes will result in a decrease of differential phase and differential amplitude distortion.

A system using video pre- and de-emphasis will transmit the higher video frequencies by phase modulation (p.m.) and the low video frequencies by low deviation f.m. and the signal-to-noise ratio can be made equal to that of an a.m. system occupying the same bandwidth. The differential phase and differential amplitude distortion will, however, be much less than would occur in an f.m. system with similar radio frequency pre- and de-emphasis but without video pre- and de-emphasis. Video pre- and de-emphasis were not used in the monochrome narrow-band f.m. system described in Section 4 of this report since it was found possible to obtain low distortion and a satisfactory signal-to-noise ratio using only radio frequency pre- and de-emphasis. However, to obtain a corresponding performance for a colour transmission system it might be necessary to use both video and r.f. pre- and de-emphasis.

3.5. Presence of Spurious Echoes of Main Signal

It has been shown[2] that the appearance of spurious echoes on a television picture is quite different for a.m. and f.m. In the field-store standards conversion process, the spurious signal is switched on and off according to a switching pattern. As has been pointed out in the Introduction, if a.m. is used, the visibility of the interference is increased due to the change in the d.c. component of the video waveform that corresponds to the switching pattern. In the case of f.m., the addition of spurious signals causes sinusoidal variations of brightness to be superimposed on the picture but no change of d.c. level results. In a subjective experiment[2] it was found that the interference was just perceptible to 50% of experienced viewers under laboratory viewing conditions if the relative level of the switched spurious signal was -34 dB in the case of f.m. and -44 dB in the case of a.m. Thus, from the point of view of picture impairment due to the presence of spurious echoes f.m. has a distinct advantage over a.m.

4. PREFERRED PARAMETERS FOR AN F.M. SYSTEM

The object of the investigation outlined in this report was to determine the parameters of a narrow-band v.s.b. f.m. transmission system whose performance is comparable with that of an a.m. system occupying the same bandwidth. The parameters derived by experiment for such a v.s.b. system are listed below for the two cases of interest in connection with field-store conversion, namely a monochrome 625-line, 50-field system having a video-frequency band of 5·5 MHz and a monochrome 525-line, 60-field system with a video-frequency bandwidth of 4·2 MHz.

PARAMETER	SYSTEM	
	625/50	525/60
Video bandwidth	5·5 MHz	4·2 MHz
R.F. bandwidth (see Fig. 1)	7·5 MHz	5·7 MHz*
Vestige bandwidth (see Fig. 1)	2·0 MHz	1·5 MHz
R.F. pre-emphasis characteristic	Flat from carrier to ± 1 MHz, rising to +12 dB at 5·5 MHz away from carrier	Flat from carrier to ± 0·8 MHz, rising to +12 dB at 4·2 MHz away from carrier
R.F. de-emphasis characteristic	Inverse of pre-emphasis characteristic	Inverse of pre-emphasis characteristic
Peak frequency deviation	± 1 MHz	± 0·8 MHz

* This is the minimum bandwidth in which a 525/60 monochrome signal could be transmitted. However, in a practical field-store converter a bandwidth of about 7·5 MHz would be available. In this case it would be possible to increase the video frequency and vestige bandwidths with a consequent reduction of response and group delay variations with frequency. The system would then have lower distortion or, alternatively, the deyia- could be increased with an improvement of perhaps 1 to 2 dB in signal-to-noise ratio.

The modulation and demodulation systems are shown in outline in Fig. 3 and the basic circuits of the modulator, limiter and discriminator are shown in Fig. 4. The modulator consisted of a conventional form of oscillator including a variable-capacity diode (varactor) in the frequency-selective circuit. The range over which the instantaneous frequency varies linearly with the applied voltage is small (of the order of 3% of centre frequency) and for carrier frequencies below about 30 MHz it is desirable to use a higher carrier frequency in the modulator process and subsequently to change frequency by beating with an appropriate constant frequency signal.

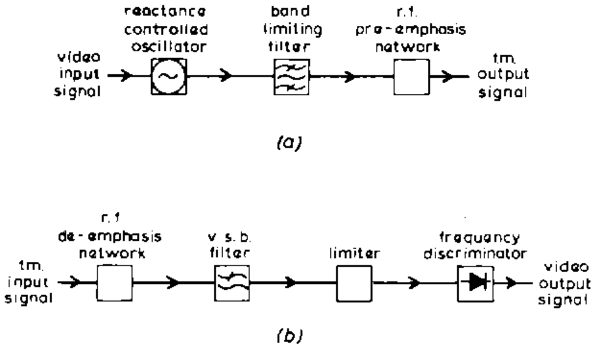

Fig. 3 - Narrow-band f.m. system
(*a*) Modulation system
(*b*) Demodulation system

The limiter consisted of four stages of amplification with back-to-back diodes across each stage. Each stage had a gain (with diodes disconnected) of about 9 dB (a figure found by experiment to give the best limiting efficiency) and the overall a.m. rejection was about 40 dB (i.e., the depth of amplitude modulation on the input is reduced by about 100 : 1).

The frequency discriminator consisted of two tuned circuits each fed with the limited r.f. signal. The centre frequencies of the two tuned circuits were just beyond the two extremes of the wanted r.f. band (i.e., just beyond carrier frequency plus or minus highest significant sideband frequency). The output signals are detected in conventional a.m. detectors whose (video) outputs are subtracted to form the output video signal. By adjustment of the parameters of the tuned circuits it is possible to produce an output characteristic which is linear over the required band and balanced about zero output. This circuit is preferable to the conventional Foster-Seeley discriminator for wide-band, low-carrier frequency systems because its adjustment is more straightforward.

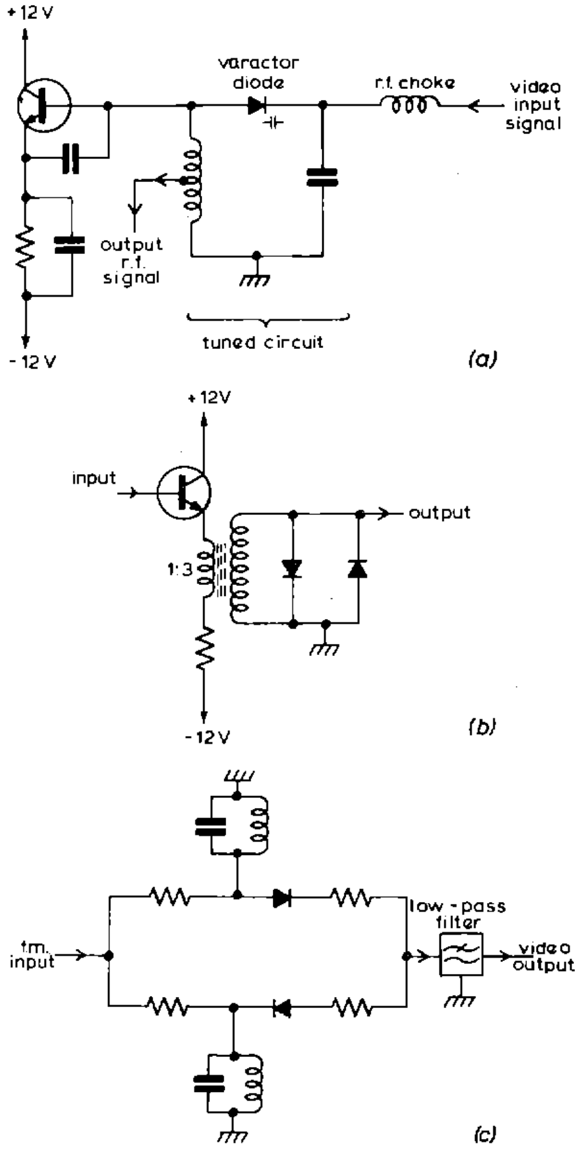

Fig. 4 - Outline circuit diagrams of f.m. system

(*a*) F.M. modulator (*b*) One stage of limiter
(*c*) Frequency discriminator

5. CONCLUSIONS

A narrow-band f.m. system using vestigial sideband transmission has been investigated, which is suitable for the transmission of television signals through the fused-quartz delays of a field-store standards conversion system. The performance of the f.m. system is comparable with that of a conventional a.m. system, occupying the same bandwidth, with respect to signal-to-noise ratio and the distortion caused by variations in the transmission characteristic with frequency. The performance of the f.m. system is superior to that of an a.m. system with regard to picture impairment due to gain variations, non-linearity and the presence of spurious echoes. It is concluded that f.m. is superior to a.m. as a modulation system for transmission of television signals through the fused-quartz delays of a field-store standards converter. It is also possible that f.m. will offer advantages in other applications which involve switching a television signal between paths having slightly different characteristics.

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APPENDIX

The Effect of the Response and Phase Characteristics of the Transmission Path in Amplitude-Modulated and Narrow-Band Frequency-Modulated Transmission Systems

Consider the transmission of a sinusoidal video signal $a \cos \omega_1 t$. The modulated radio-frequency signal may be expressed in complex form as:

$$e^{j\omega_0 t}(1 + \delta_1 \cos \omega_1 t) \qquad \text{for a.m.}$$

$$e^{j(\omega_0 t + \delta_2 \sin \omega_1 t)} \qquad \text{for f.m.} \qquad (1)$$

where $\delta_1 = a$ and $\delta_2 = ka/\omega_1$ and k is a constant having suitable dimensions such as radians per second per volt if a is in volts. The radio frequency signals of Expression (1) may be written in terms of sidebands as:

$$\frac{\delta_1}{2} e^{j(\omega_0 - \omega_1)t} + e^{j\omega_0 t} + \frac{\delta_1}{2} e^{j(\omega_0 + \omega_1)t} \qquad \text{for a.m.}$$

$$-\frac{\delta_2}{2} e^{j(\omega_0 - \omega_1)t} + e^{j\omega_0 t} + \frac{\delta_2}{2} e^{j(\omega_0 + \omega_1)t} \qquad \text{for f.m.} \; (2)$$

where it is assumed that δ_2 is sufficiently small for sidebands of higher order than the first to be neglected. The radio-frequency signals of Expressions (2) are transmitted through a network of transfer characteristic $R(\omega)e^{j\theta(\omega)}$ where $R(\omega)$ is the response/frequency characteristic and $\theta(\omega)$ the phase/frequency characteristic. The radio-frequency signals of Expressions (2) are modified in amplitude and phase by the network and may be written:

$$e^{j\omega_0 t + j\theta_0}\left[1 + \frac{\delta_1}{2}\frac{R_{-1}}{R_0} e^{-j\omega_1 t + j(\theta_{-1} - \theta_0)} + \frac{\delta_1}{2}\frac{R_1}{R_0} e^{j\omega_1 t + j(\theta_1 - \theta_0)}\right] \qquad \text{for a.m.}$$

$$R_0 e^{j\omega_0 t + j\theta_0}\left[1 - \frac{\delta_2}{2}\frac{R_{-1}}{R_0} e^{-j\omega_1 t + j(\theta_{-1} - \theta_0)} + \frac{\delta_2}{2}\frac{R_1}{R_0} e^{j\omega_1 t + j(\theta_2 - \theta_0)}\right] \qquad \text{for f.m.} \quad (3)$$

In Expressions (3) R_{-1}, R_0, R_1, θ_{-1}, θ_0 and θ_1 represent $R(\omega_0 - \omega_1)$, $R(\omega_0)$, $R(\omega_0 + \omega_1)$, $\theta(\omega_0 - \omega_1)$, $\theta(\omega_0)$ and $\theta(\omega_0 + \omega_1)$ respectively.

If δ_1 is sufficiently small, an envelope detector will demodulate the a.m. signal of (3) to give:

$$1 + \frac{\delta_1}{2}\frac{R_{-1}}{R_0}\cos\left[\omega_1 t - \theta_{-1} + \theta_0\right] + \frac{\delta_1}{2}\frac{R_1}{R_0}\cos\left[\omega_1 t + \theta_1 - \theta_0\right] \qquad (4)$$

The term R_0 represents the response at d.c. Thus relative to the response at d.c., the a.c. output from the detector will be:

$$\frac{a}{2}\frac{R_{-1}}{R_0}\cos(\omega_1 t - \theta_{-1} + \theta_0) + \frac{R_1}{R_0}\cos(\omega_1 t + \theta_1 - \theta_0) \qquad (5)$$

since $\delta_1 = a$.

In the case of f.m., the term in brackets in Expression (3) may be re-written in the form $re^{j\phi}$ and the output of a balanced f.m. discriminator will be proportional to the time derivative of ϕ and the d.c. term will be suppressed. Since δ_2 has been taken to be small, $d\phi/dt$ can be shown to be:

$$\frac{\omega_1\delta_2}{2}\frac{R_{-1}}{R_0}\cos(\omega_1 t - \theta_{-1} + \theta_0) + \frac{\omega_1\delta_2}{2}\frac{R_1}{R_0}\cos(\omega_1 t + \theta_1 - \theta_0) \qquad (6)$$

Substituting for δ_2 gives:

$$k\,\frac{a}{2}\left[\frac{R_{-1}}{R_0}\cos(\omega_1 t - \theta_{-1} + \theta_0) + \frac{R_1}{R_0}\cos(\omega_1 t + \theta_1 - \theta_0)\right] \qquad (7)$$

Expressions (5) and (7) are in the constant ratio k and the demodulated signal is thus seen to have the same form in the a.m. and f.m. cases provided the modulation depth (in the case of a.m.) and the modulation index (in the case of f.m.) are small. The modulation index is inversely proportional to the modulating frequency and must therefore become large at very low frequencies. However, the modulating frequency at which the second order and higher order sidebands become significant can be made arbitrarily low by choosing a sufficiently low deviation. As a result, the frequency range in which the second and higher-order sidebands are significant can be confined to the region in which the quasi-stationary approximation is valid. Thus at very low frequencies the a.m. and f.m. systems perform differently. The advantage lies with the latter since the distortion due to imperfections in the transmission path vanishes.

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